A High Specific Output Gasoline Low-Temperature Combustion Engine

– 2018 US DOE VTO AMR meeting –

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GENERAL MOTORS

Project ID # acs121

Overview

Timeline

Start Date: January 2017
End Date: December 2019
Duration: 3 years

Completion: 50%

Goals / Barriers

- 15 ~ 17% fuel economy over baseline
- Low temperature combustion regimes for gasoline engines
- Effective engine controls for Low Temperature Combustion
- Emissions control challenges for advanced engine concepts

Budget

Total funding for 3 years
$ 1.90 M DOE Share
$ 2.04 M GM Share
$ 3.94 M Total

Funding received in FY17: $ 209,994
Funding for FY18: $ 583,917

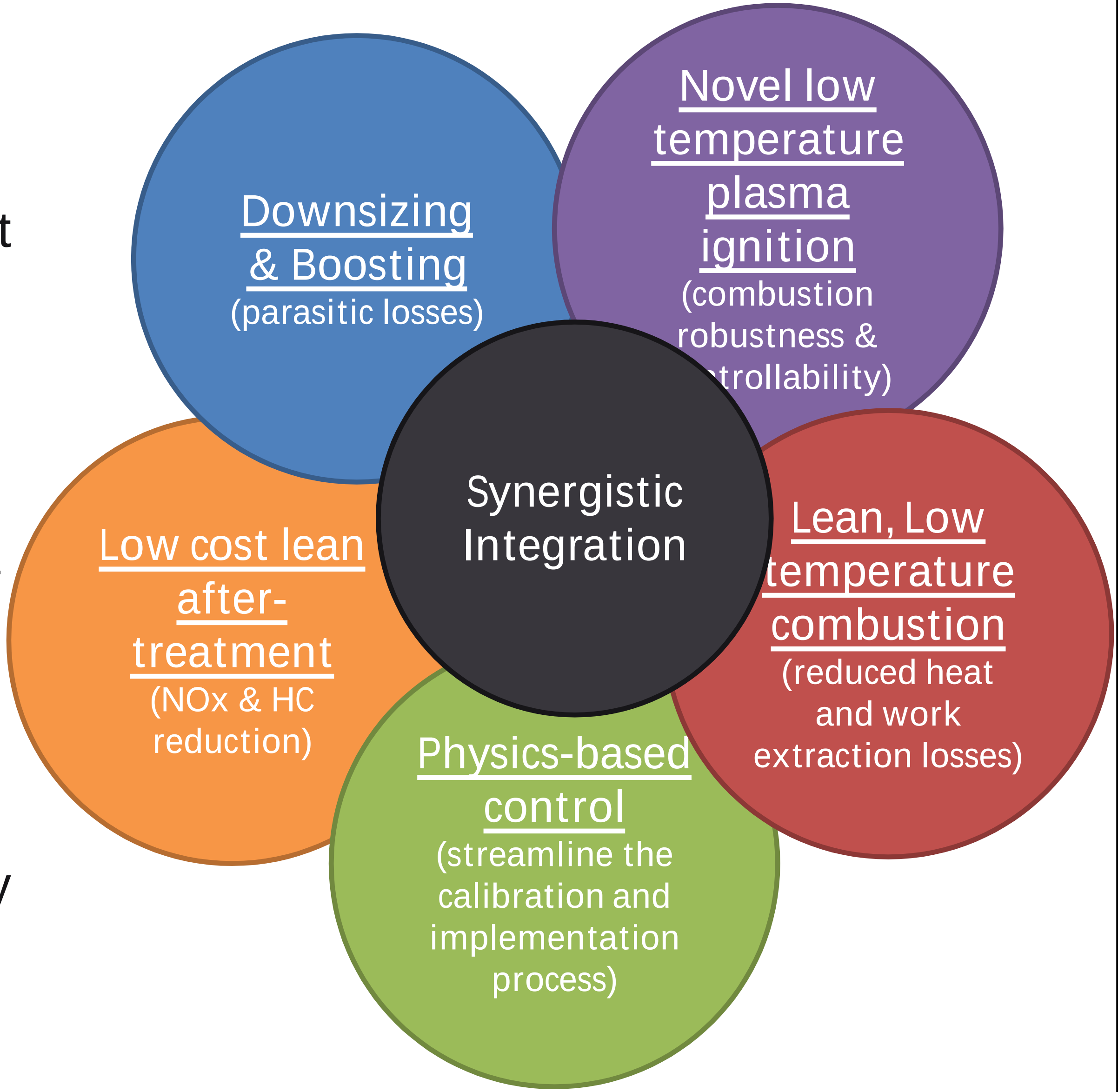
Project Partners

Key Suppliers

FEV	Delphi
Honeywell	BMTS
Federal Moguls	BASF

Relevance – Objectives

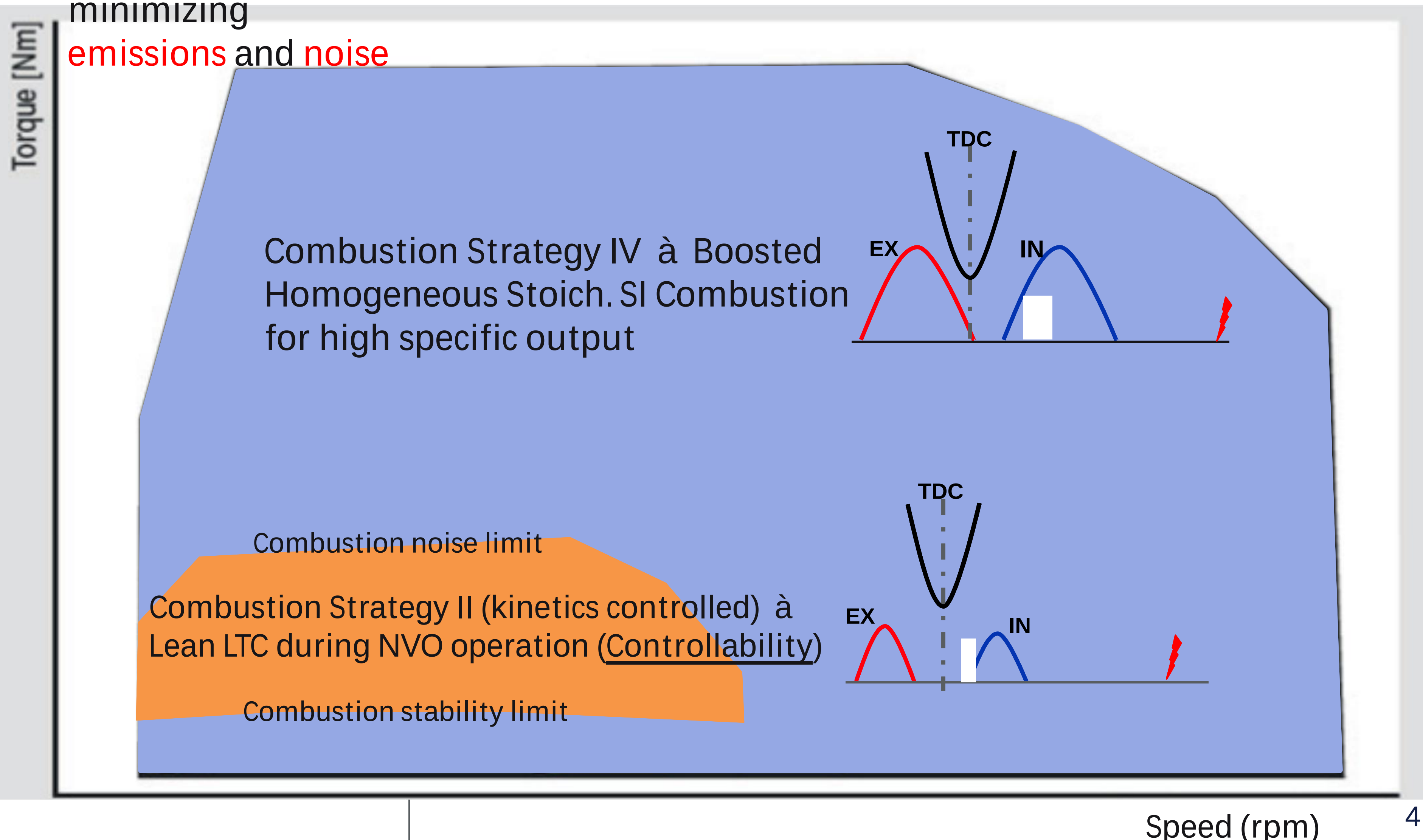
- Develop a gasoline combustion engine system to demonstrate a 15-17% fuel economy improvement relative to a contemporary stoichiometric combustion engine using marketplace gasoline (RD587)
- Be consistent with relevant emissions constraints (Target: SULEV 30 regulation)
- Integrate the enabling technologies synergistically



Approach – LTC Strategy

Goal: maximize efficiency and controllability while minimizing emissions and noise

Obstacles: *limited operating ranges* and *difficulty in combustion timing control*



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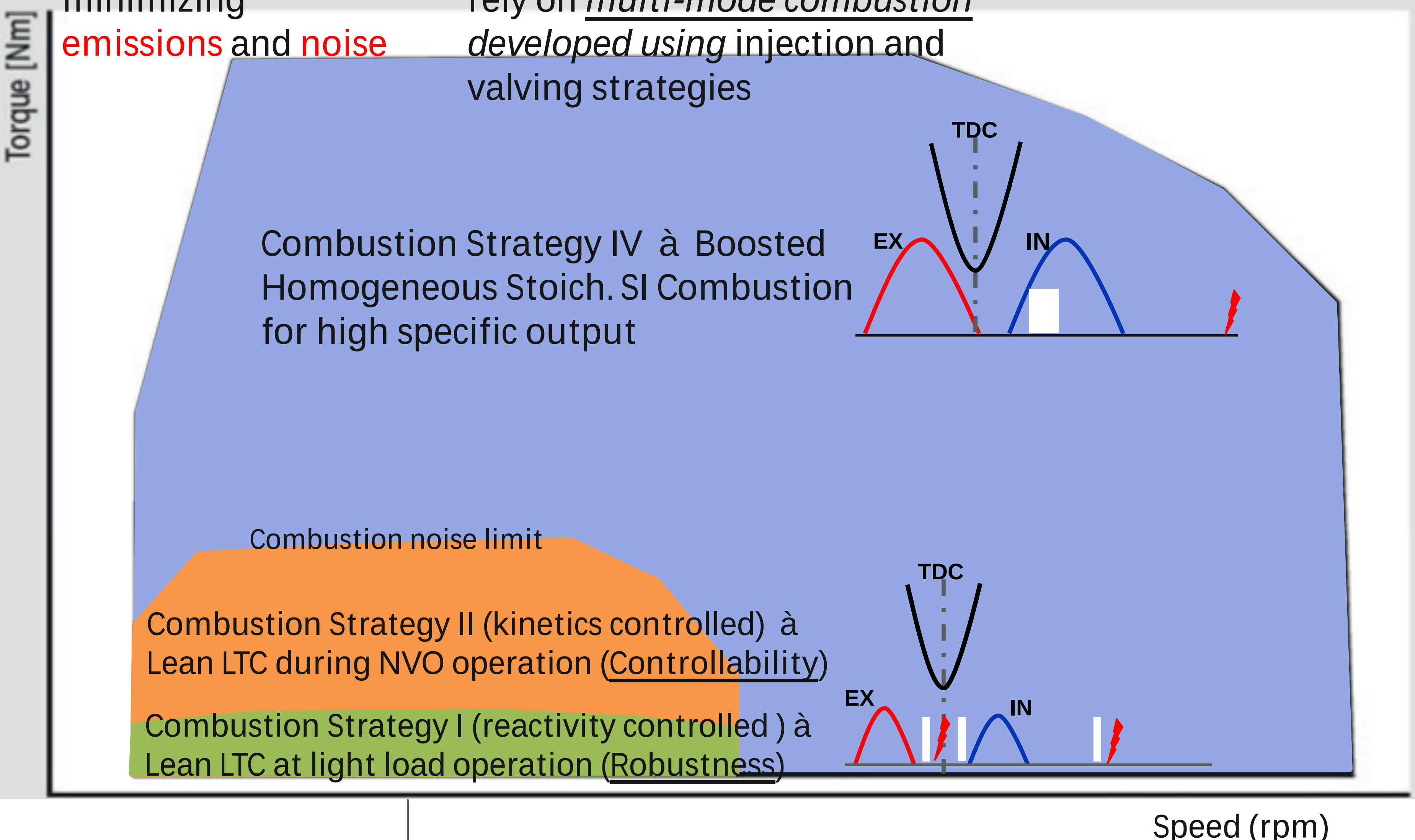

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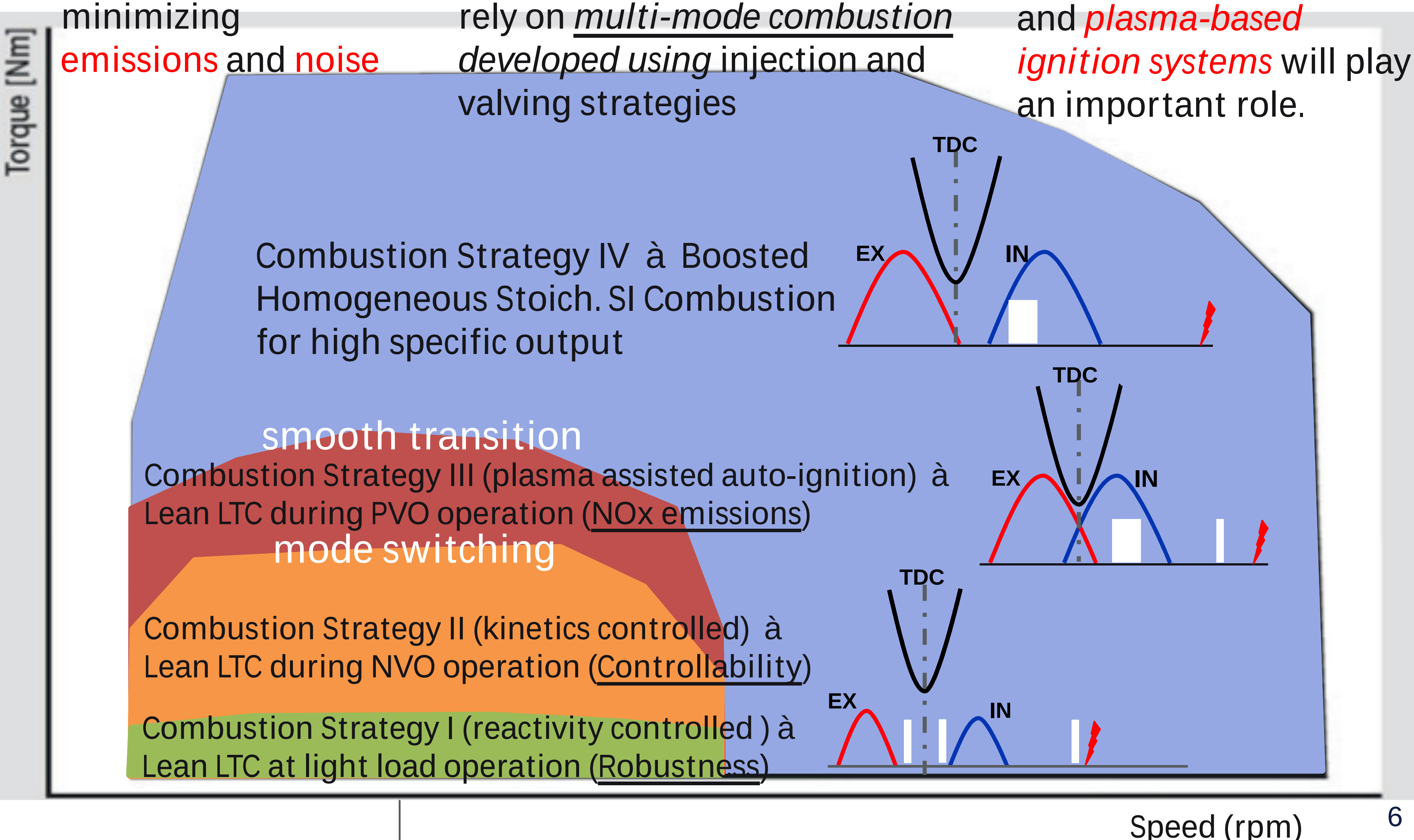
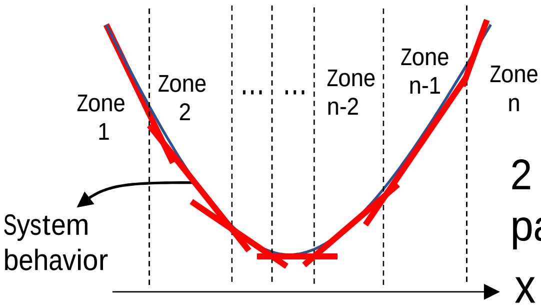
Precise transient control over all conditions à *physics-based controls* and *plasma-based ignition systems* will play an important role.



Approach – Physics-based Control

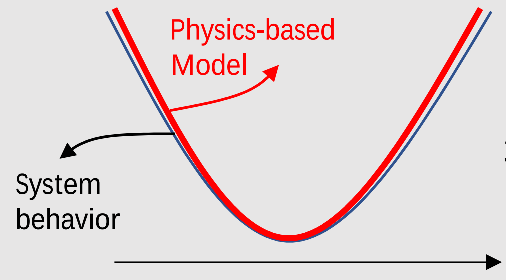


$Y_{MODEL} = a_k\, x + b_k$
$(k = 1,2, \ldots, n)$

2 x n parameters

Control with regression model

à Fidelity of the model is proportional to the number of the tuning parameters à More parameters require more calibration data and effort



$Y_{MODEL} = a\, x^2 + b\, x + c$

3 parameters

Control with physics-based model

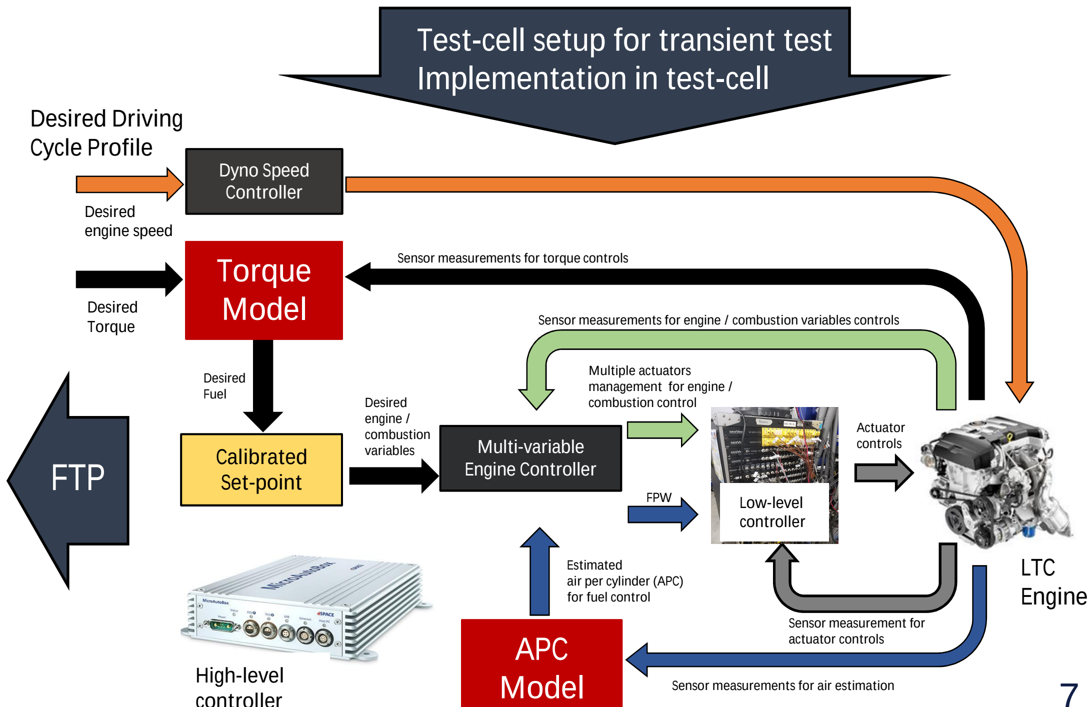
à The number of the tuning parameters is minimal without compromising performance

Physics-based engine control significantly reduces calibration efforts by minimizing tuning parameters

Demonstration of engine control with physics-based control

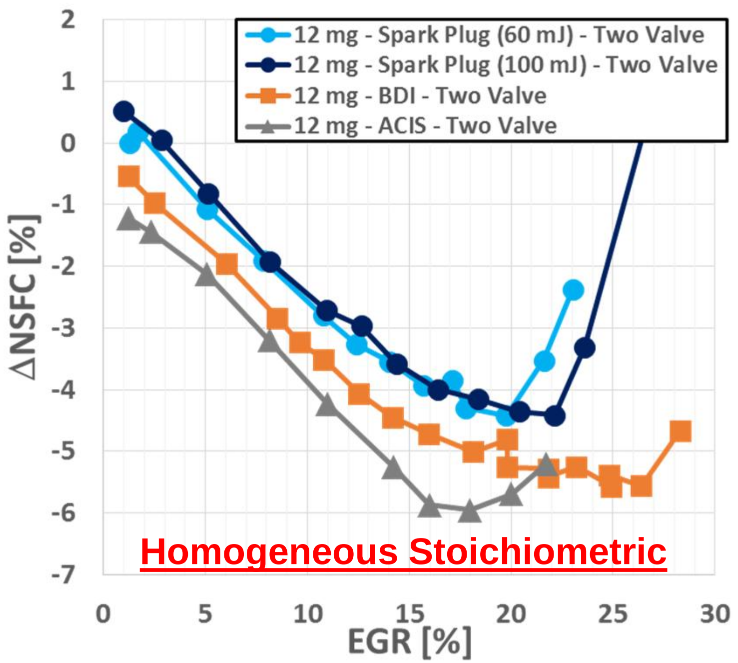
à Fuel economy analysis based on experimental FTP data from test-cell

à Demonstrate engine control with reduced development time without compromising transient performance

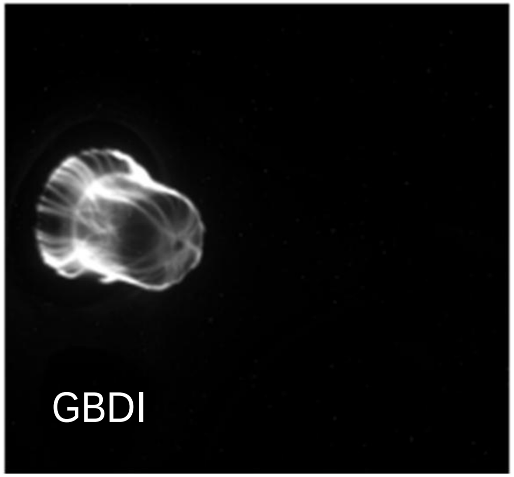


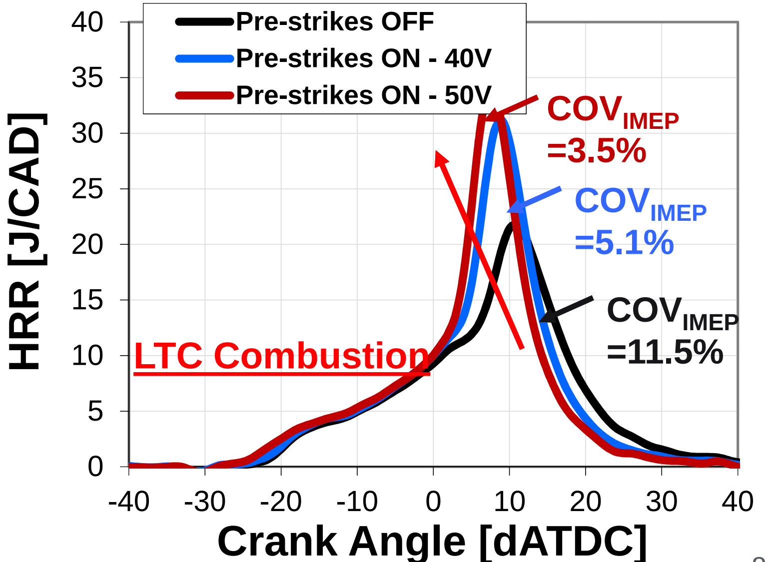
Approach – Low Temperature Ignition

- Challenge: the higher in-cylinder pressures (down-sized and boosted engine) demands higher breakdown voltages à require smaller gap sizes à the more the stability limit is degraded.



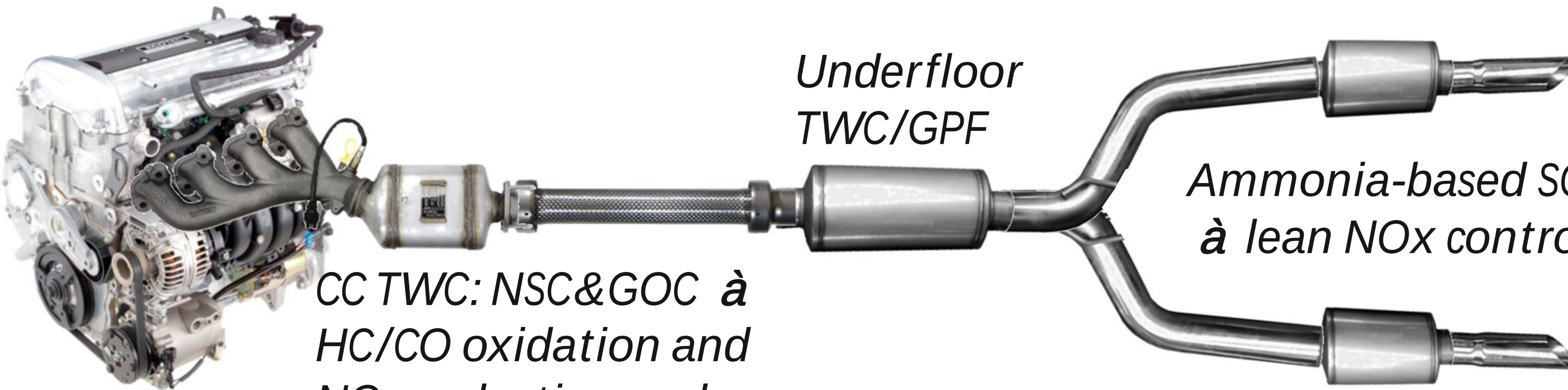
- GM in conjunction with Federal Mogul has developed a unique GBDI (Groundless Barrier Discharge Igniter).





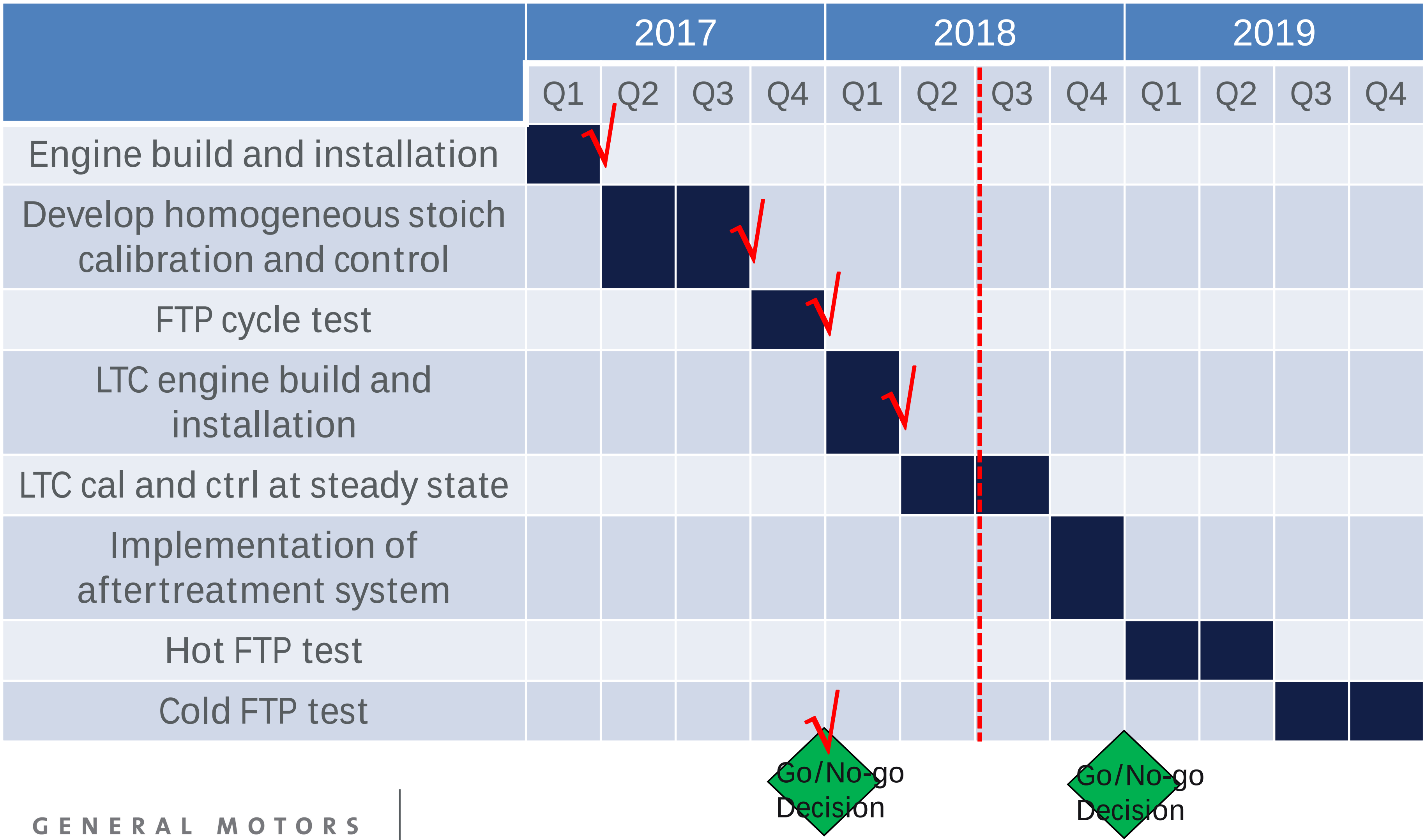
- The system provides superior flame-initiation under homogeneous stoichiometric conditions, as well as LTC combustion phasing control through ozone generation by simply changing the supplying voltages *without adding undue complexity and/or jeopardizing NOx emissions*.

Approach – PASS (Passive Ammonia SCR System) Aftertreatment



1. PASS is a low cost, lean aftertreatment system that relies on the intrinsic performance characteristics of the TWC and SCR to address stoichiometric and lean exhaust gas aftertreatment *without the need for supplemental urea injection and/or high PGM loadings*.
2. Periodically operate the engine rich to generate NH3 on the TWC and store it on the SCR à Under lean conditions, use the stored NH3 on the SCR for NOx conversion.

Approach – Milestones



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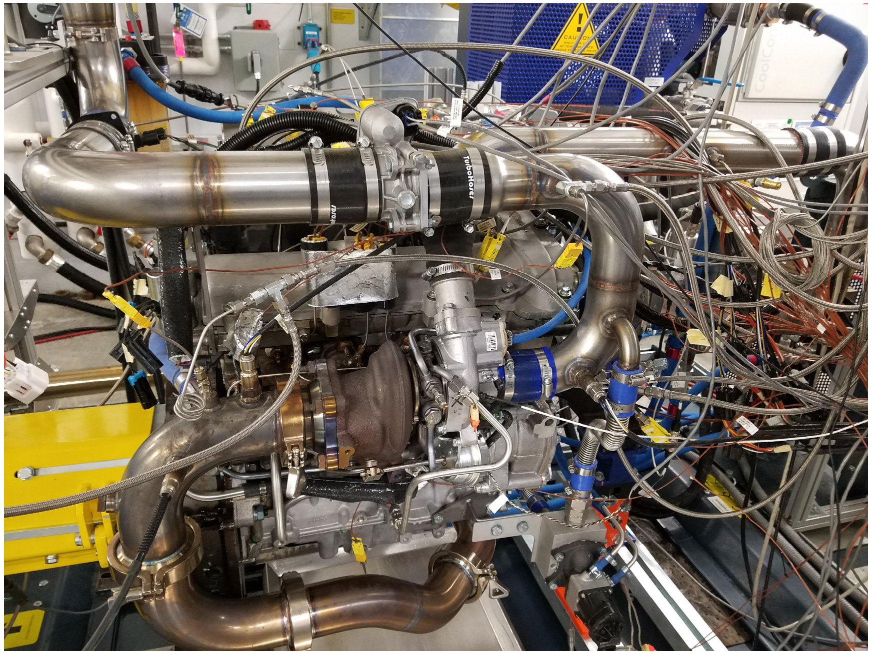
Technical Accomplishments and Progress



LTC Engine

- Scaled 1.4L 4-cylinder turbo-charged engine
- DELPHI 60/90-10 hole injector
- GBDI Igniter
- Two-step camshaft
- VGT

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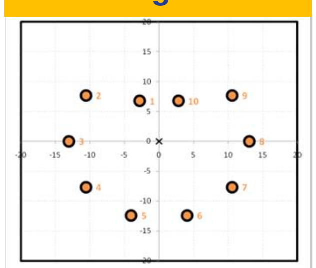
60/90deg-10hole

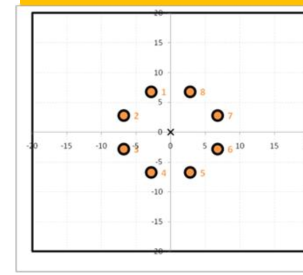


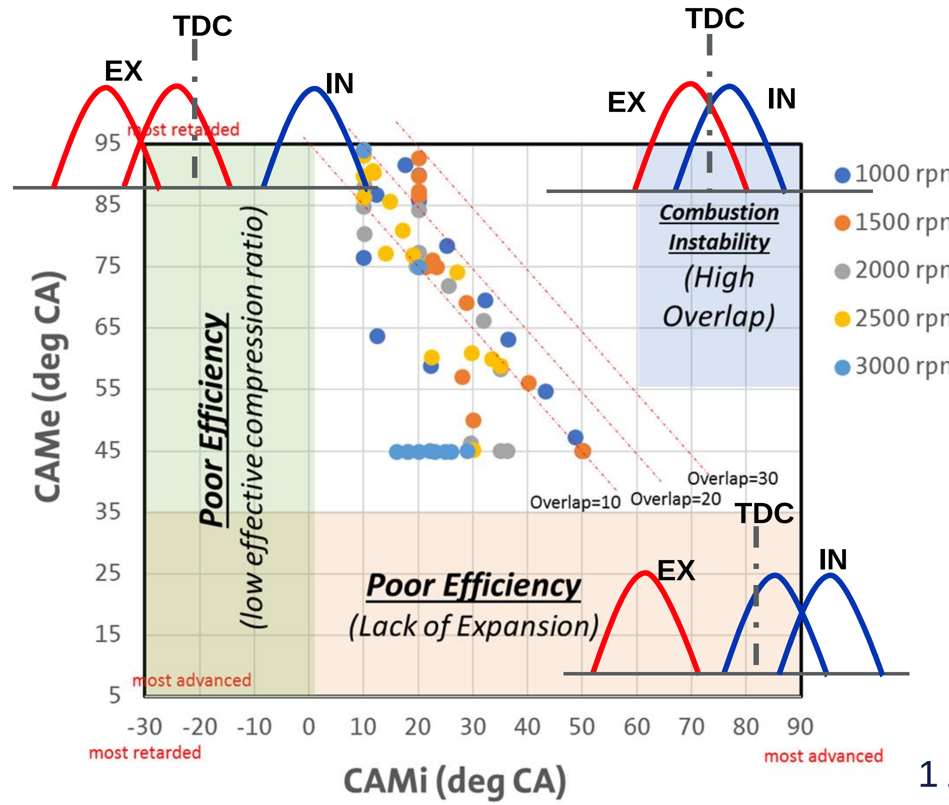
Baseline Engine

2.2L 4-cylinder Engine

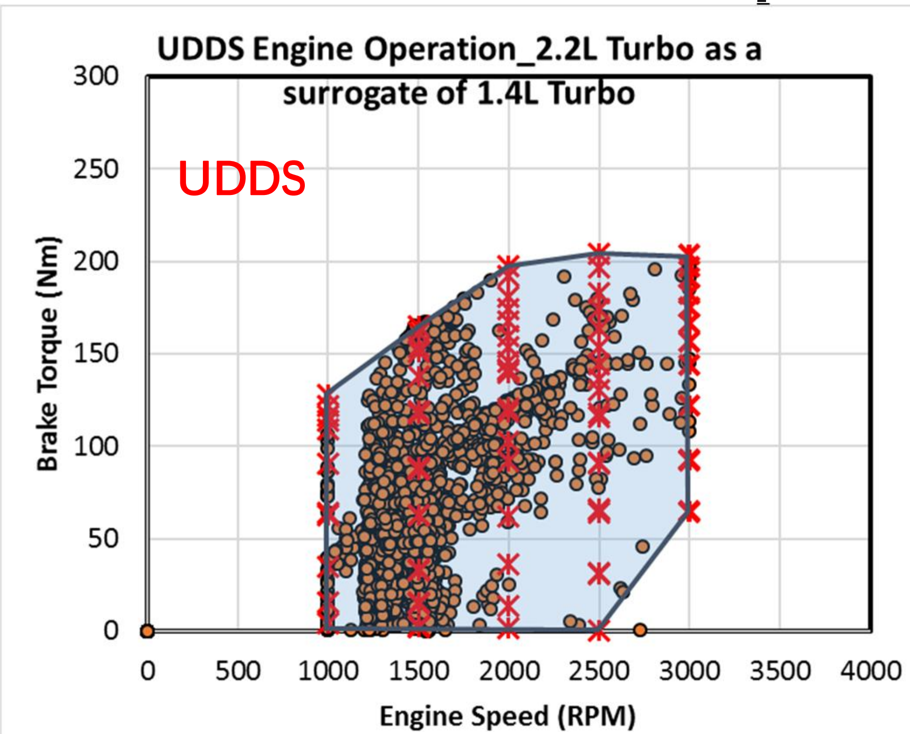
- Compression ratio = 12:1
- BOSCH 60-8 hole injector
- Conventional spark plug
- Single-step camshaft

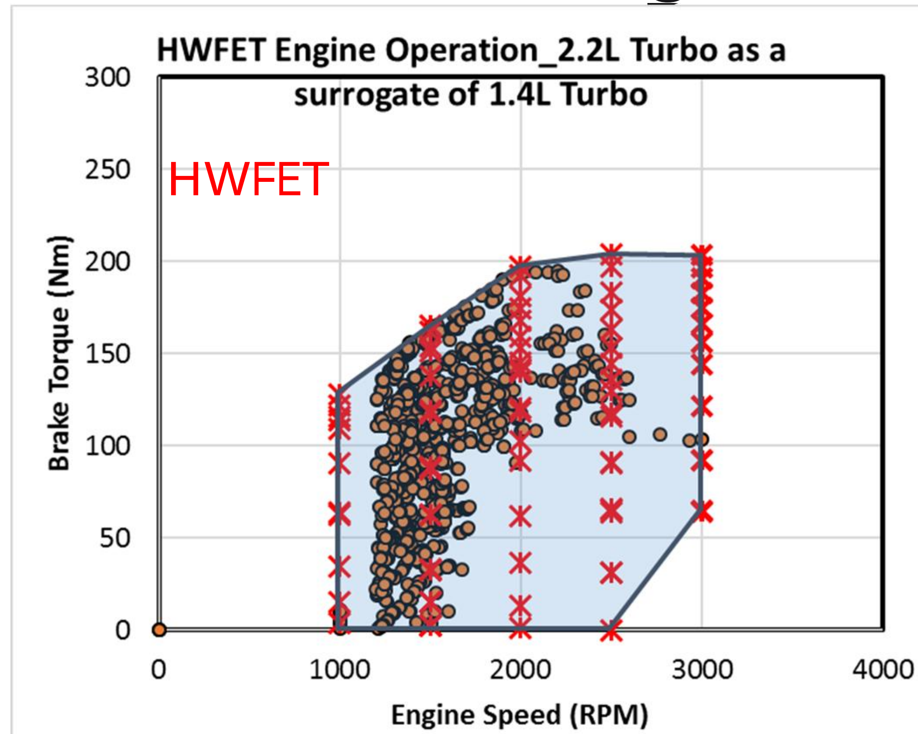
60deg-8hole

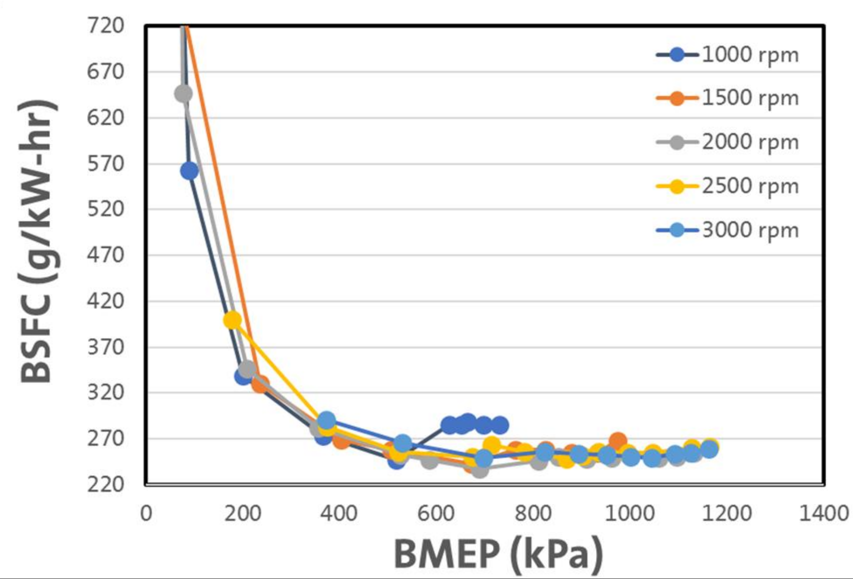




Technical Accomplishments and Progress





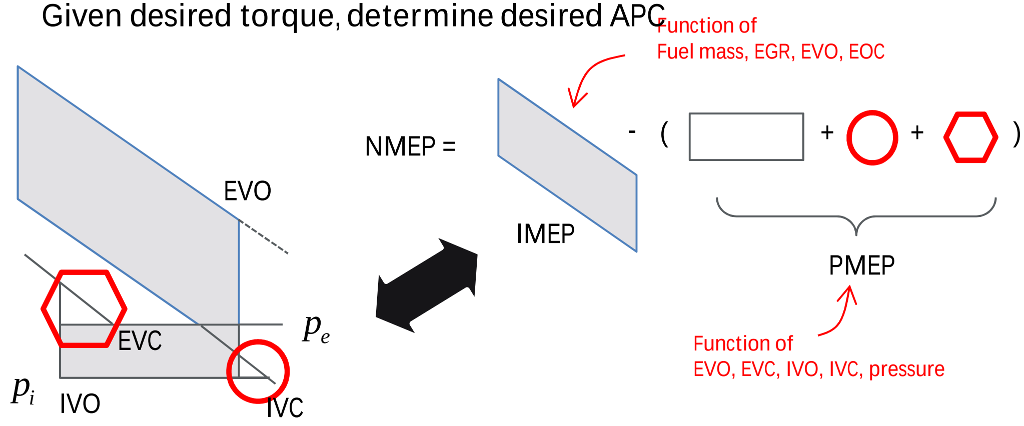


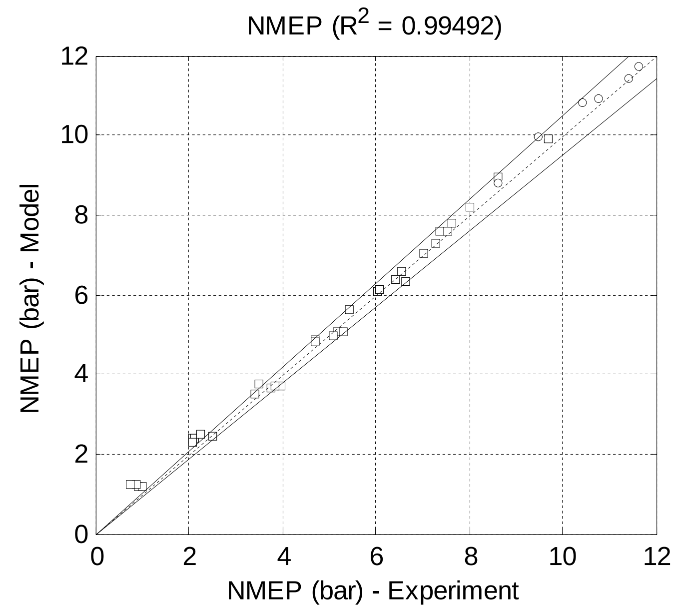
- These data will serve as the reference baseline for the upcoming lean low temperature combustion system development
- Also some of the high load points will be used even in LTC transient test

Technical Accomplishments and Progress

Net engine torque is modeled based on PV diagram

- Expressed in terms of cylinder volume at valve opening and closing timings
- Given desired torque, determine desired APC





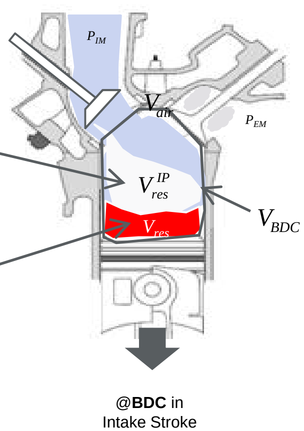
APC (Air Per Cylinder) is modeled by dynamically tracking volumes of burned gas in the cylinders

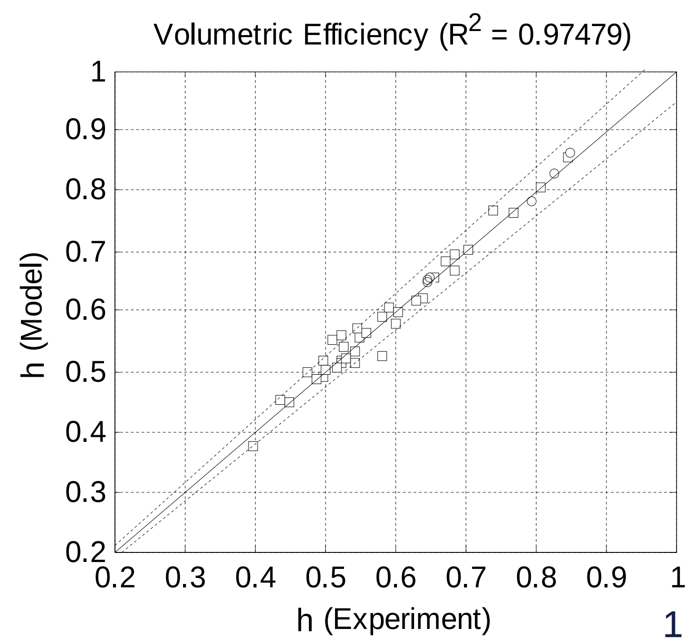
Total residual gas volume at BDC

Residual gas volume pushed to the intake port in the previous cycle and re-inducted in the present cycle
à Depend on intake valve timing

+

Residual gas volume from the present cycle
à Depend on exhaust valve timing





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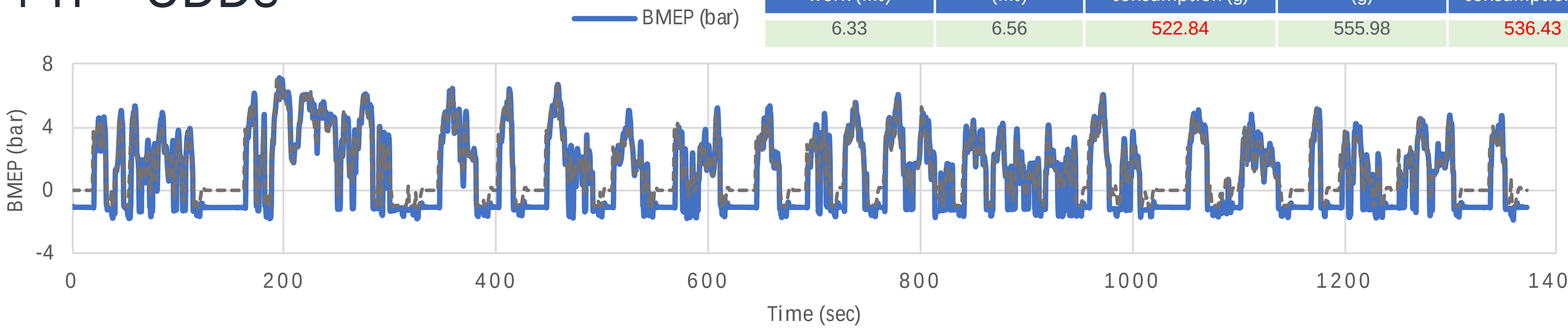
$$V_{BDC} = V_{res} + V_{res}^{IP} + V_{air}$$

Technical Accomplishments and Progress

Transient control demonstration over FTP

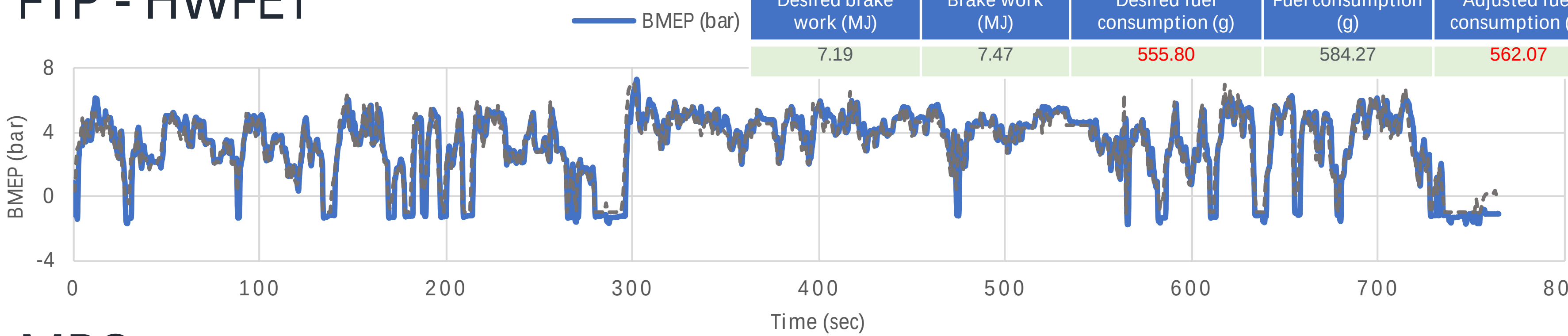
FTP - UDDS

Desired brake work (MJ)	Brake work (MJ)	Desired fuel consumption (g)	Fuel consumption (g)	Adjusted fuel consumption (g)
6.33	6.56	522.84	555.98	536.43



FTP - HWFET

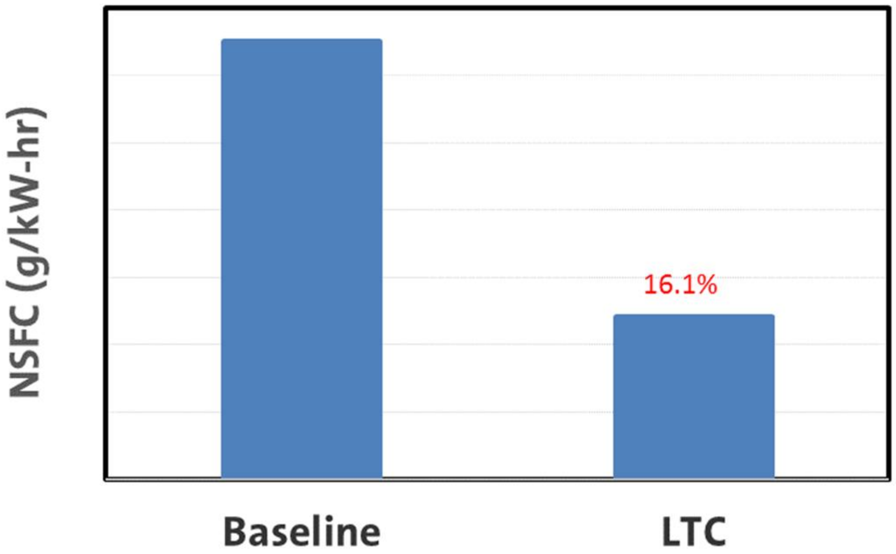
Desired brake work (MJ)	Brake work (MJ)	Desired fuel consumption (g)	Fuel consumption (g)	Adjusted fuel consumption (g)
7.19	7.47	555.80	584.27	562.07



MPG

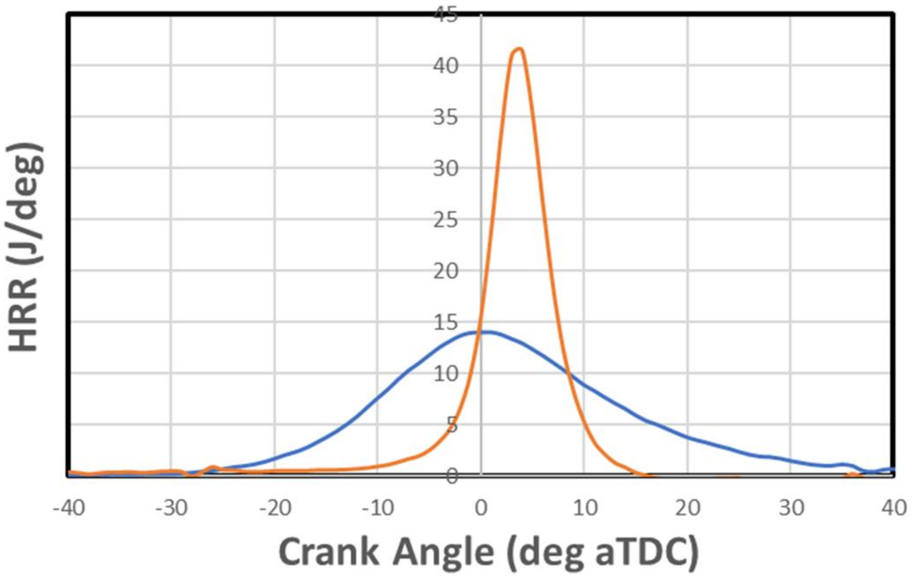
Driving Cycle	Desired fuel consumption (gallon)	Adjusted fuel consumption (gallon)	Desired MPG	Measured MPG
UDDS	0.1847	0.1896	40.60	39.57
HWFET	0.1964	0.1986	52.24	51.66

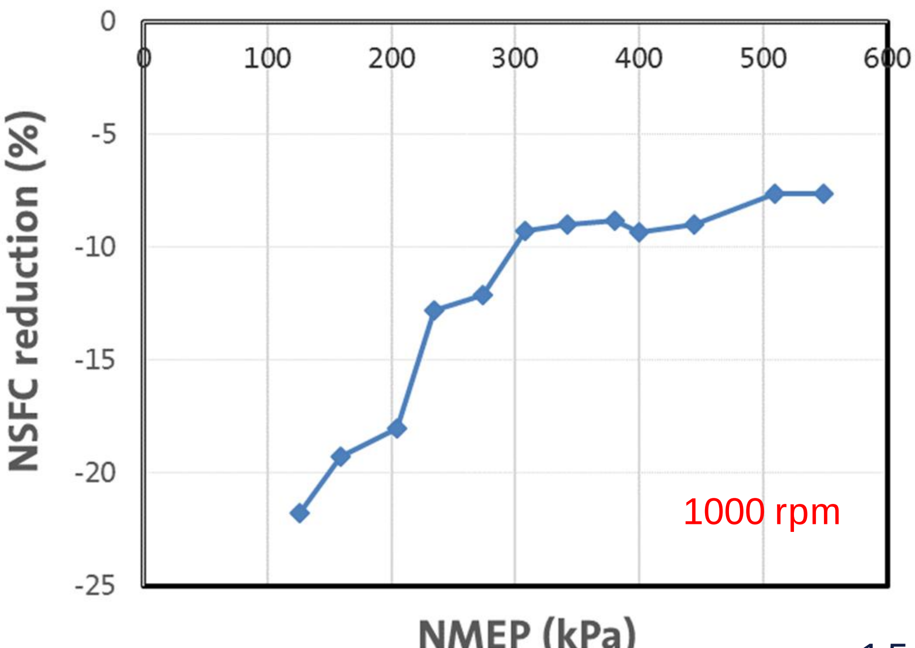
Technical Accomplishments and Progress



Efficiency Benefit of LTC

- 2000 rpm, 2 bar NMEP
- Stoich SI vs lean LTC (AF=20)
- EINOx = 0.2 g/kg_f





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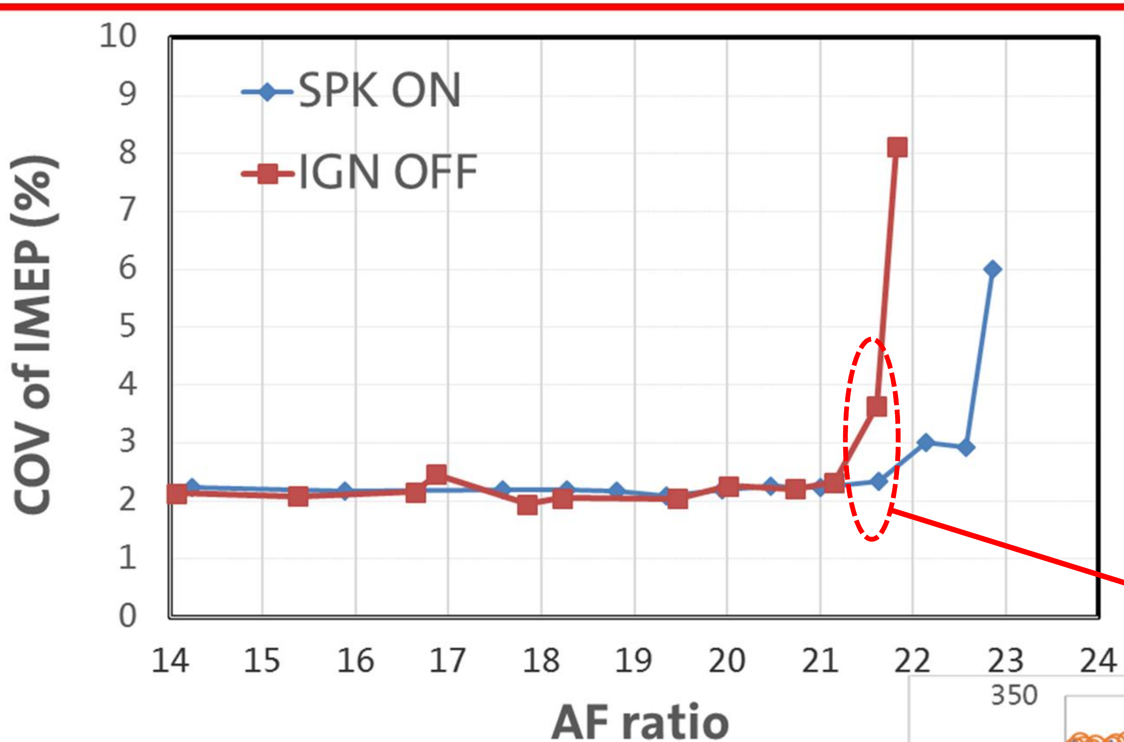
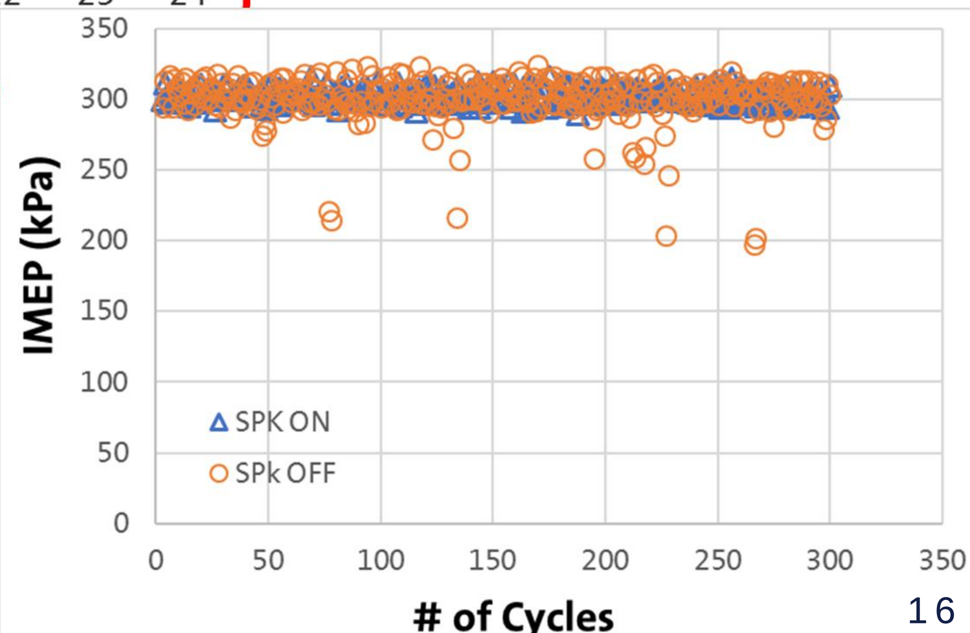


Ignition system is required for high load operation for a high specific output à what about LTC regime?

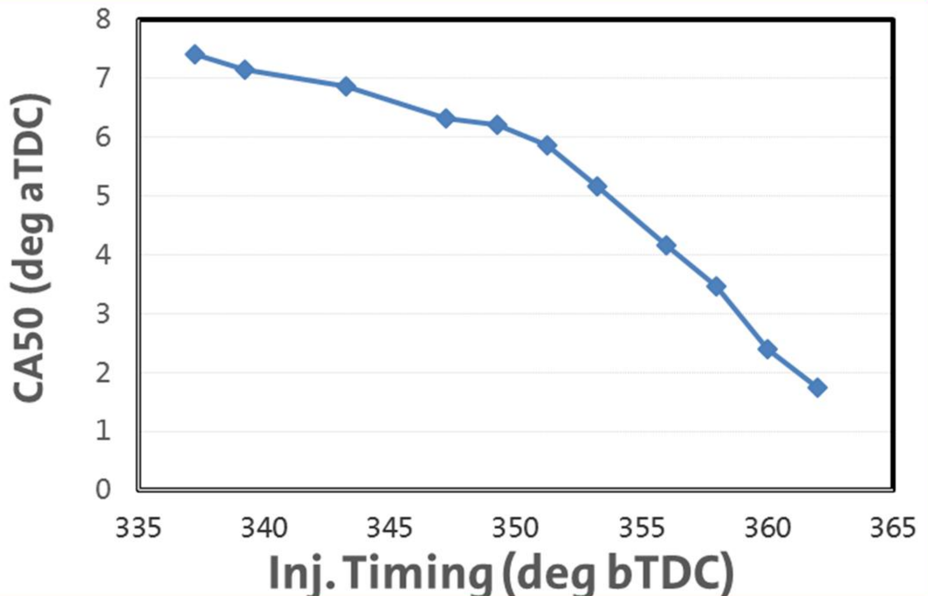
Effect of Ignition on LTC

- 2000 rpm, 2 bar BMEP
- CA50 = 5 aTDC
- Extend the lean limit (wider stable operating ranges)



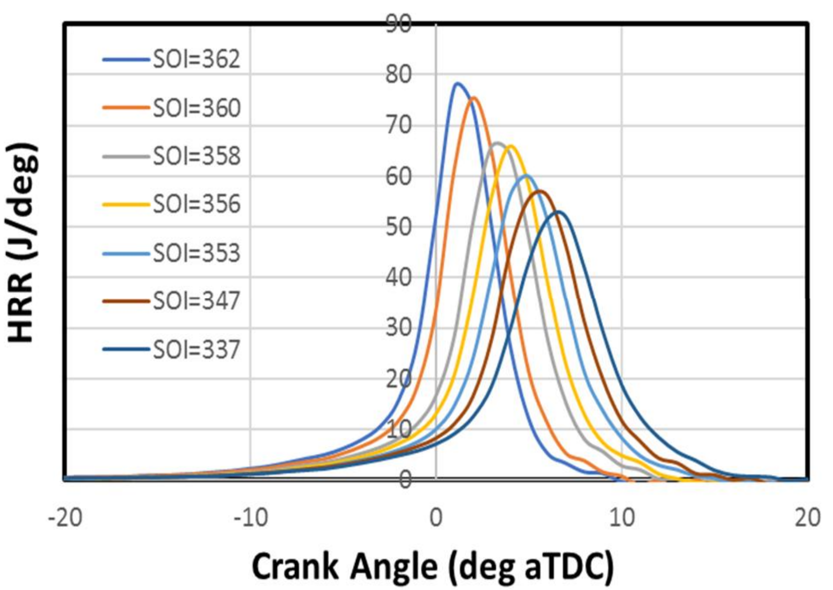
Spark ignition provides stability by limiting “problematic” cycles à it does not drive combustion, but it provides stability

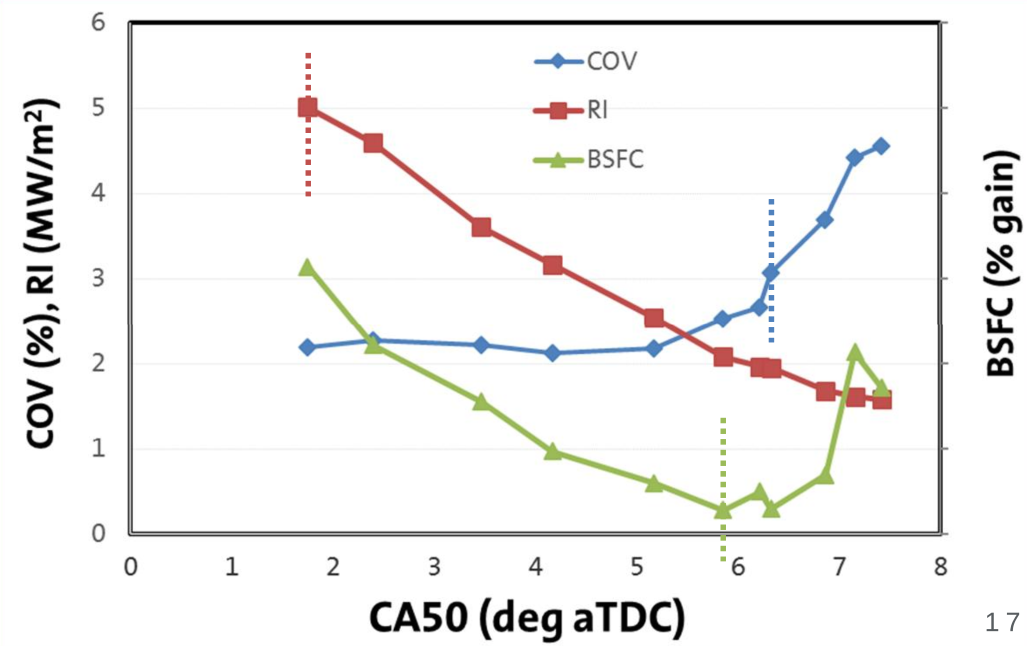
Technical Accomplishments and Progress



Ignition Timing Controllability

- 2000 rpm, 2 bar BMEP, AF=20
- Fixed SPK at 55 deg bTDC
- The most advanced CA50 is limited by combustion noise and the most retarded CA50 is determined by combustion stability.





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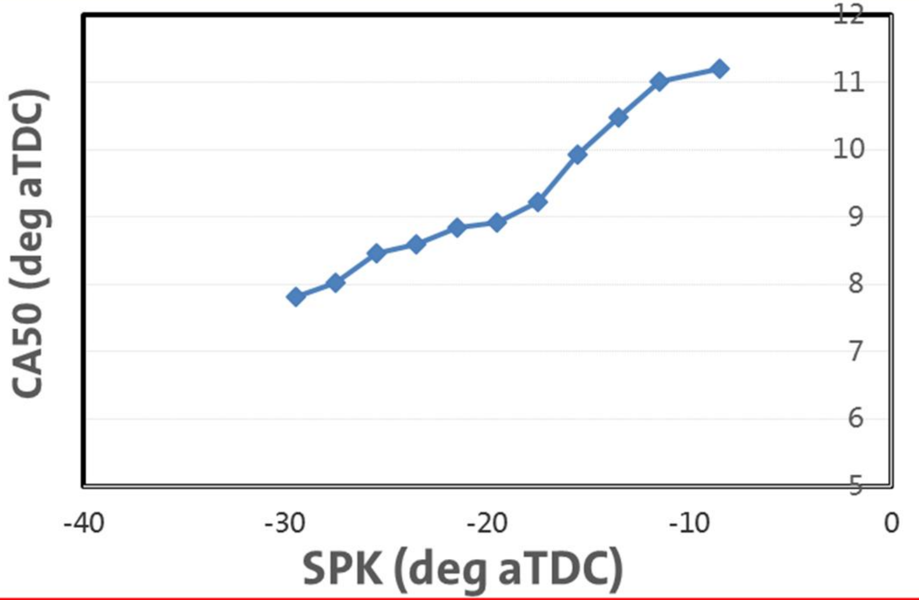
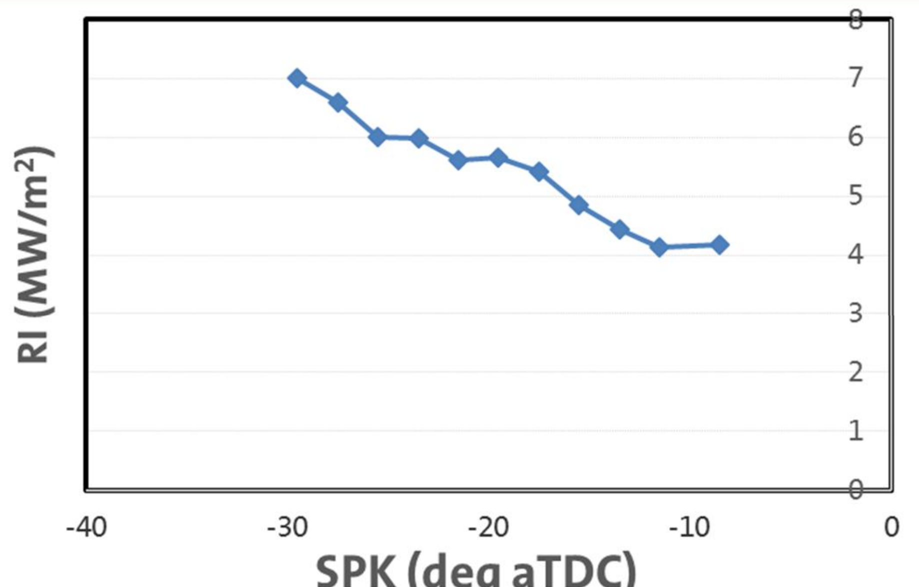
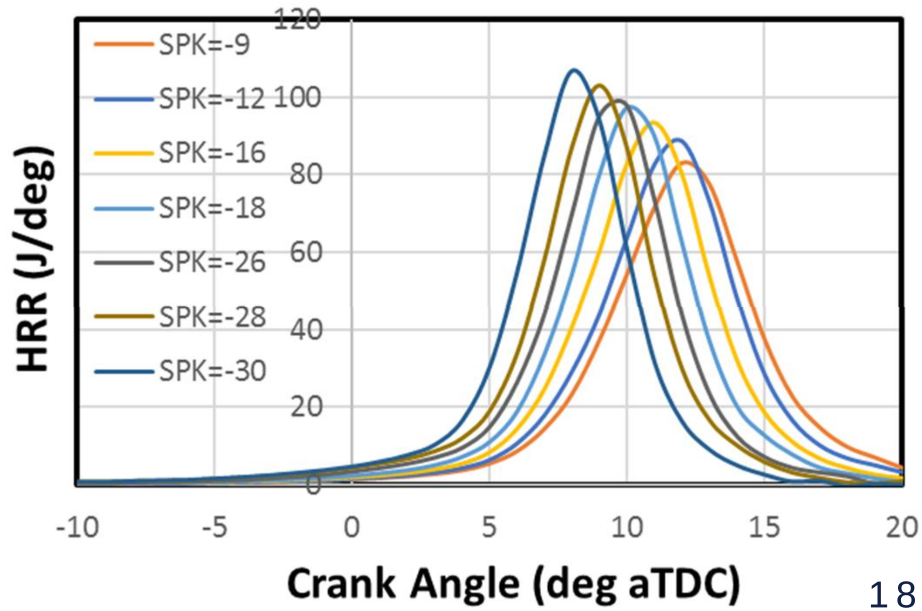


Ignition Timing Controllability

- 2000 rpm, 4 bar BMEP
- Double Injection; 75/25 Split
- Combustion noise can be reduced by retarding combustion phasing using spark timing while maintaining combustion stability





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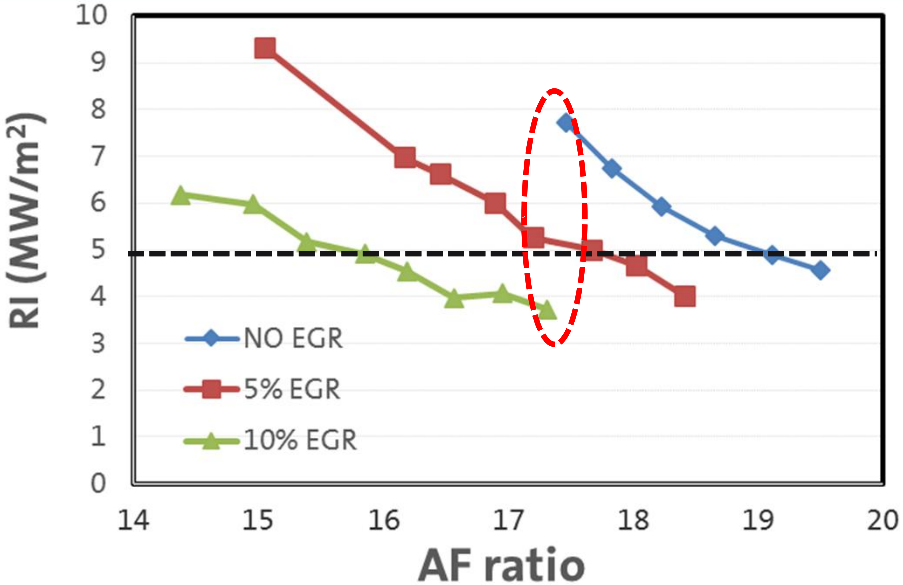
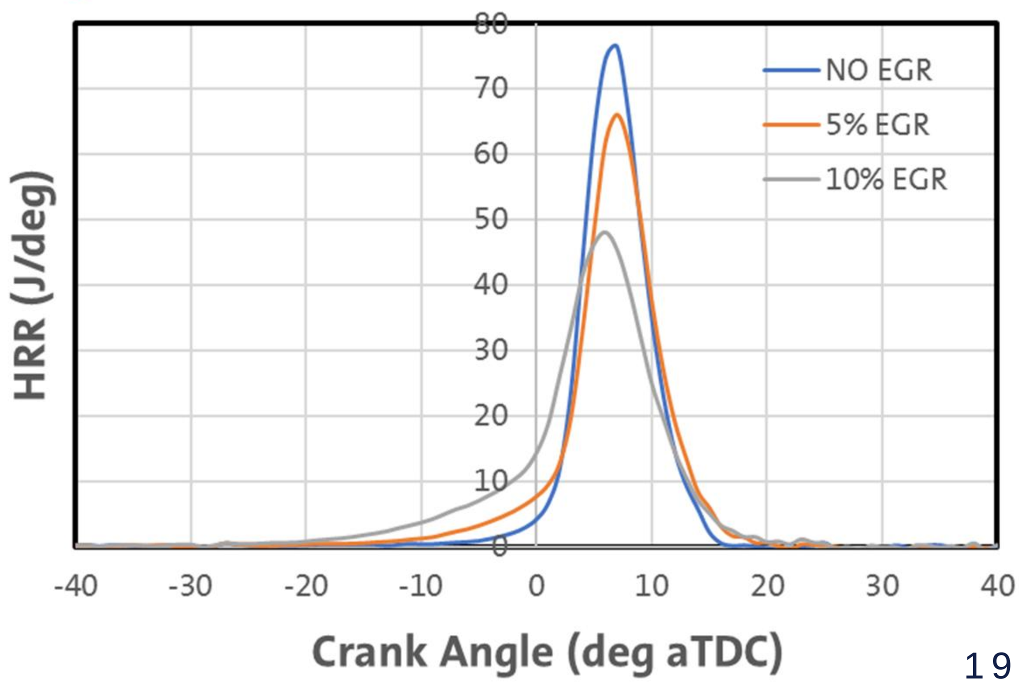


Noise Reduction (Effect of EGR)

- 2000 rpm, 3.3 bar BMEP
- CA50 = 7 deg aTDC

EGR suppresses auto-ignitability of the mixture à combustion begins with flame-burn and auto-ignition takes place later in the cycle à the total burn duration is extended à ringing decreases



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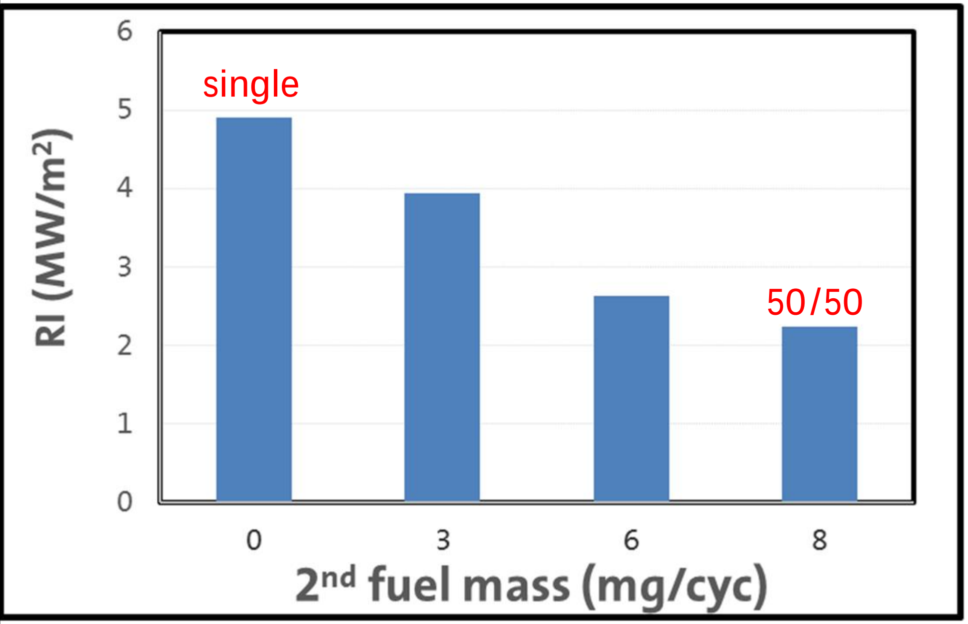
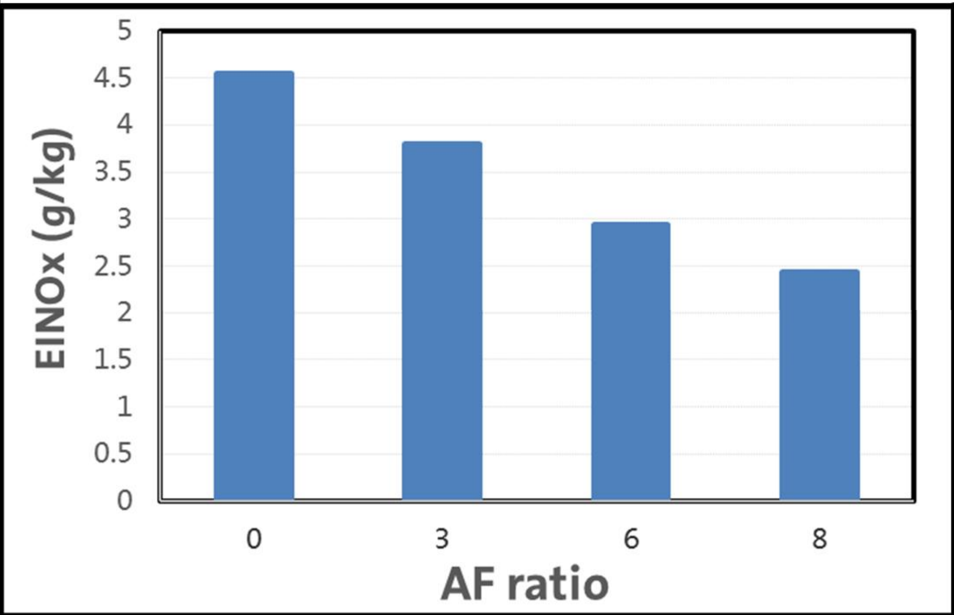
Technical Accomplishments and Progress

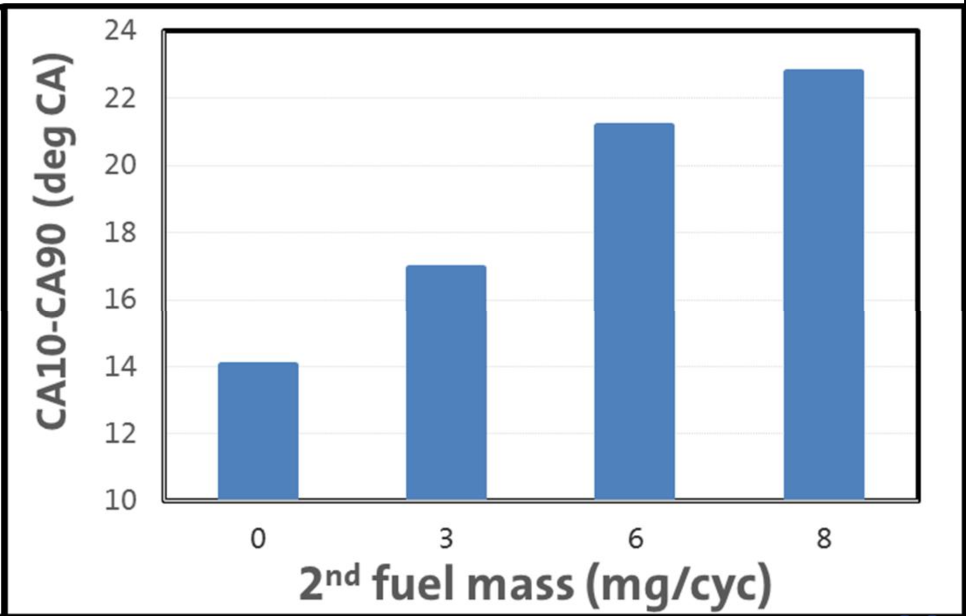


Noise Reduction (Effect of Multiple Injection)

- 2000 rpm, 4 bar BMEP
- CA50 = 9.5 aTDC
- 10% EGR

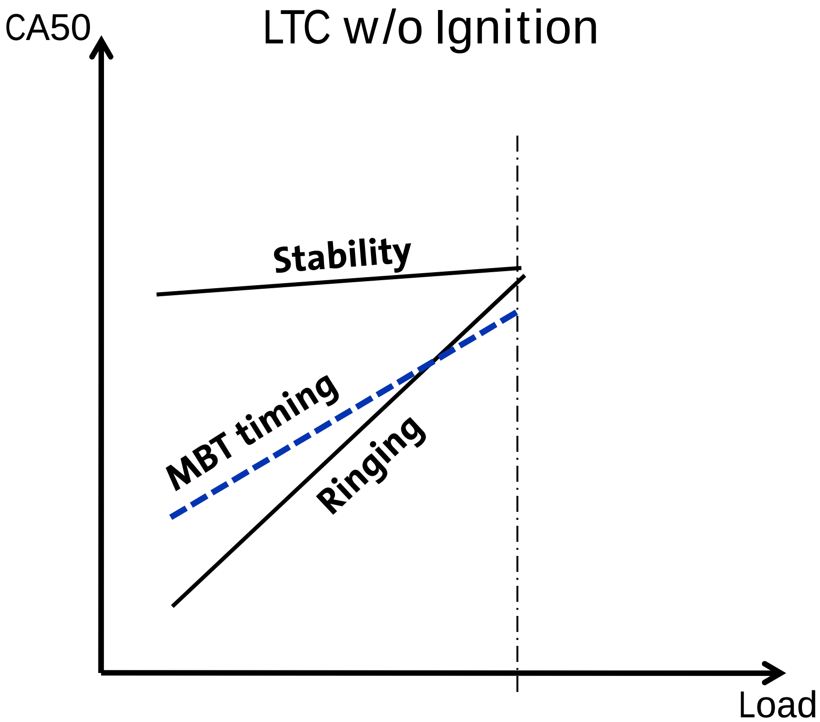
à The more mass for 2nd injection, the lower ringing and NOx emissions due to the extended burn duration





Technical Accomplishments and Progress

Lean LTC operating range was successfully extended using ignition, multiple injection, EGR and valving strategy



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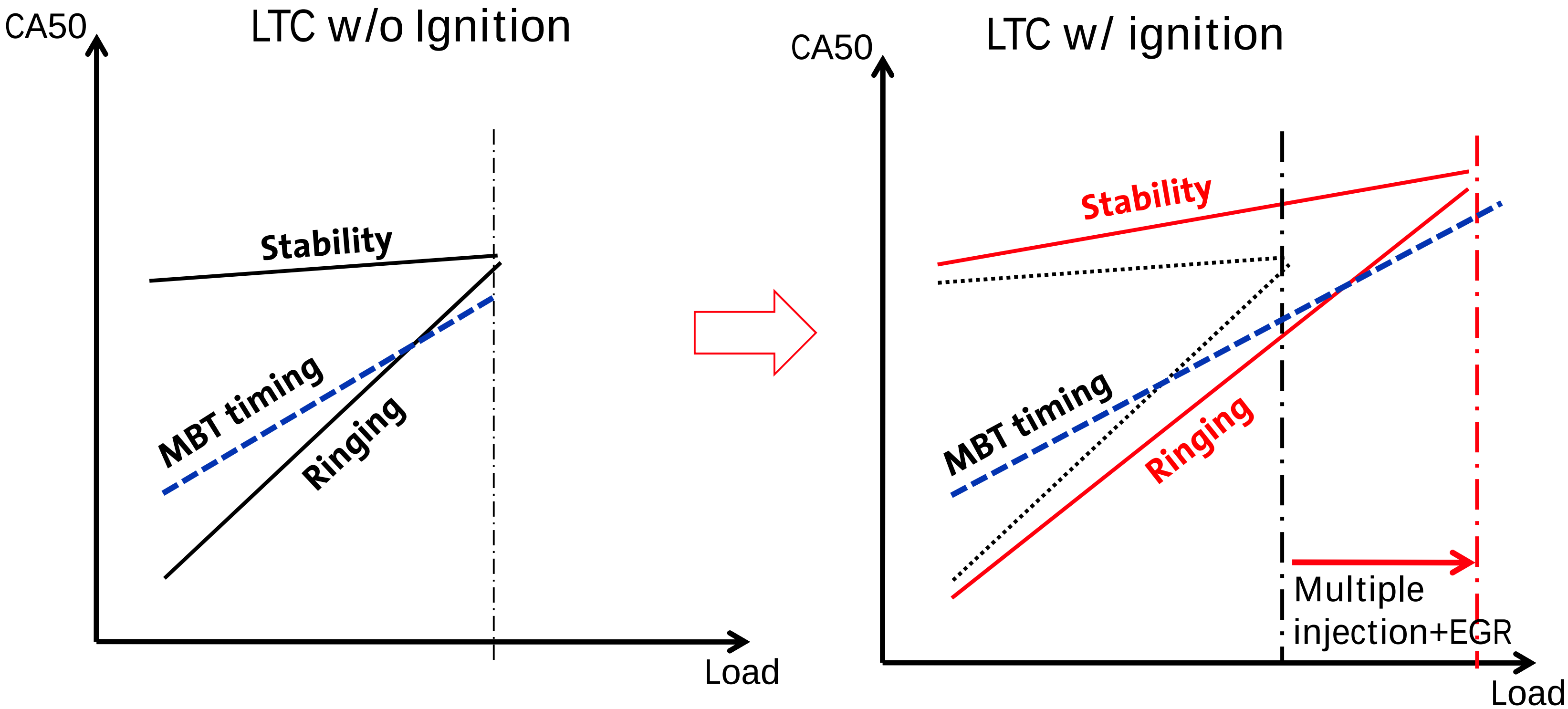

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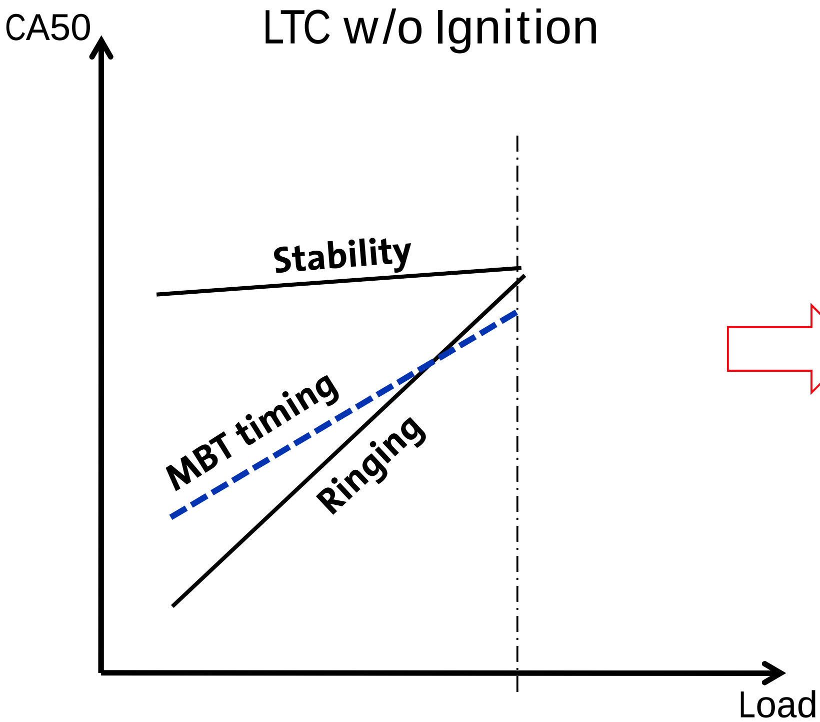
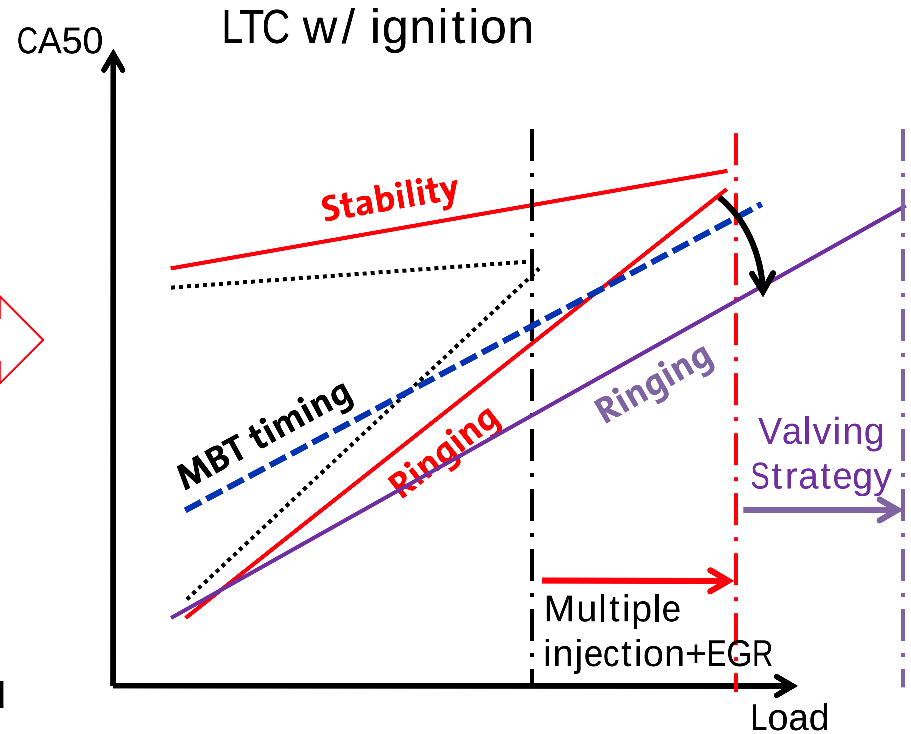
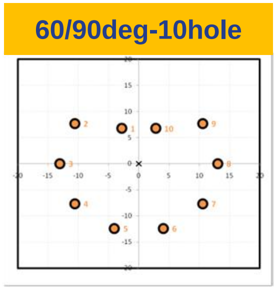
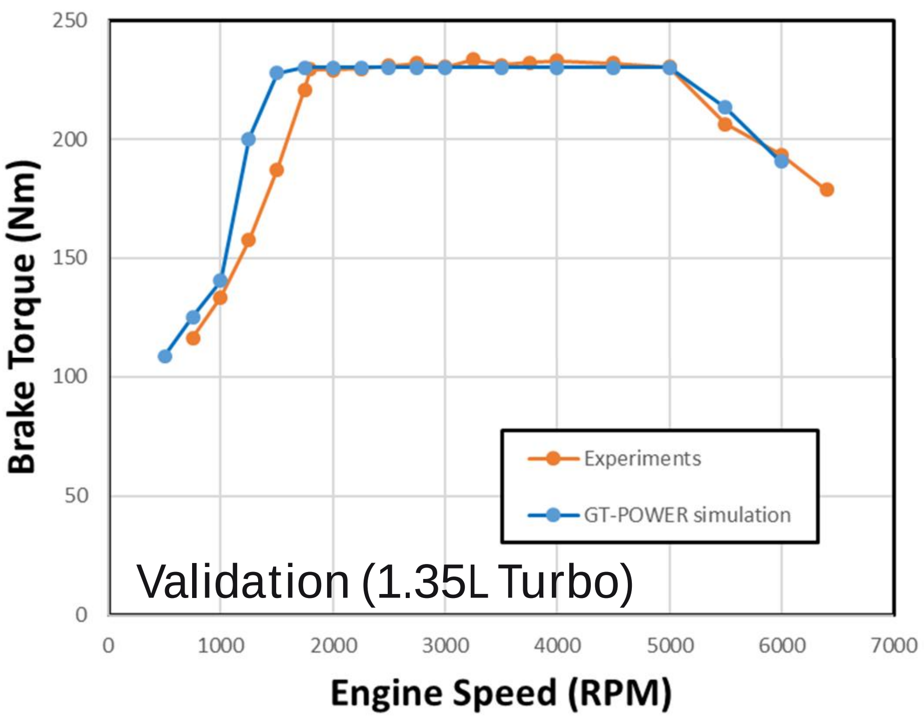


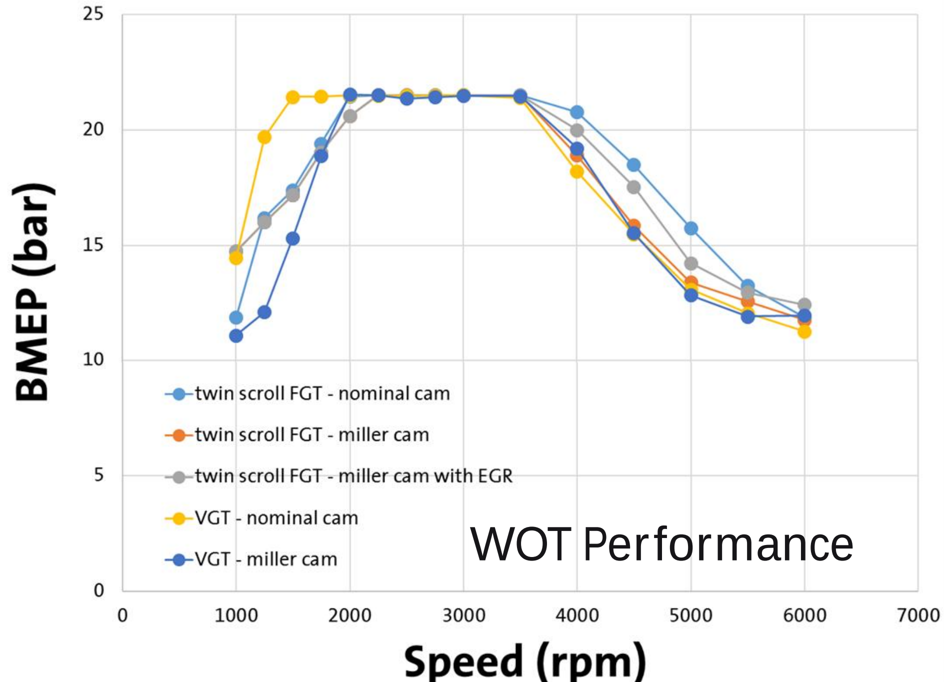


Collaboration and Coordination

- FEV – GT-POWER modeling support for WOT studies to reduce baseline calibration efforts and hardware risk
- DELPHI – Fuel injector supplier due to the better performance of closely-spaced multiple injection.
- Federal Mogul – Worked together for the development of GBDI
- Honeywell & BMTS – Variable Geometry Turbo supplier
- BASF – Worked together for the development of aftertreatment system







Remaining Challenges and Barriers

- Transient operation using low temperature plasma ignition system
- Develop a noise control strategy for EGR mismatching during transient operation
- Develop a seamless mode switching strategy to prevent misfire or partial burn during mode change
- Development of emissions control strategy for cold operation – efficiency gain will depend on the performance of aftertreatment system

Proposed Future Work

FY 2018

- Develop spark-based low temperature combustion at key steady-state conditions
- Develop GBDI-based full LTC calibrations to cover FTP cycles as much as possible
- Develop a seamless mode switching strategy
- Implement aftertreatment systems

FY 2019

- Refine low temperature combustion, control, and aftertreatment with GBDI during transient operation
- Demonstrate robust operation over hot FTP – fuel economy benefits and emissions results consistent with objectives
- Demonstrate robust operation over cold FTP – fuel economy benefits and emissions results consistent with objectives

Summary

Low Temperature Combustion Engine

- Complete the development of homogeneous stoichiometric SI calibration and controls
- Successfully demonstrate FTP cycle test (both UDDS and HWFET) for homogeneous stoichiometric SI operation
- Verify the efficiency benefits of low temperature combustion
- Develop the methodology of combustion phasing control for various modes of low temperature combustion
- Extend the lean low temperature combustion regime using multiple injection, EGR and valving strategy

Thank You !!!